

SUPER-DROPLET APPROACH TO SIMULATE PRECIPITATING TRADE-WIND CUMULI – COMPARISON OF MODEL RESULTS WITH RICO AIRCRAFT OBSERVATIONS

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1. INTRODUCTION

In this study we present a series of Large Eddy Simulations (LES) employing the Super-Droplet Method (SDM) for representing aerosol, cloud and warm-rain microphysics (Shima, 2008; Shima et al., 2009). SDM is a particle-based and probabilistic Monte-Carlo type model. The particle-based formulation helps to overcome the problem of parameterisation of processes occurring at single-particle scale (micro- to millimetres) as source/sink terms in the LES equations solved on grids with cell dimensions of the order of tens of metres. The aim of this paper is to showcase the capabilities and point out the limitations of SDM in context of simulation of a field of precipitating clouds.

2. THE SUPER-DROPLET METHOD

The framework of the method consists of two mutually coupled simulation components: (i) a fluid flow solver computing (in an Eulerian sense) the evolution of fluid velocity field and evolution of the thermodynamic scalar quantities, and (ii) a particle-tracking logic computing (in a Lagrangian sense) evolution of physical coordinates and physicochemical properties of a population of particles. The coupling between the Eulerian and Lagrangian components is bi-directional. The Lagrangian component feeds on the fluid velocity field in order to update the positions of super-droplets, and the thermodynamic fields to compute the condensational growth or evaporation rates. The Eulerian component feeds on the water vapour and heat source/sink rates resulting from condensation and evaporation of water on the particles. Although mutually coupled, the Eulerian and Lagrangian computations are decomposed, in the sense that they happen sequentially and the state vectors of one component are constant from the standpoint of the other (within a time-step).

The model does not differentiate between aerosol particles, cloud droplets, drizzle or rain

drops. Each particle in the model (referred to as super-droplet) represents a multiplicity of real-world particles of the same size and of the same chemical composition. From the standpoint of the Lagrangian component, the super-droplets are subject to three processes besides advection: (i) gravitational settling, (ii) condensational growth/evaporation and (iii) collisional growth. Consequently, the model covers representation of such cloud-microphysical processes as: cloud condensation nuclei (CCN) activation; drizzle formation by collisions of cloud droplets (autoconversion); accretion of cloud droplets by drizzle drops and raindrops, as well as coalescence of these larger hydrometeors (self-collection); and precipitation of drizzle and rain including aerosol wet deposition. Analogous particle-based techniques were recently used in context of simulations of precipitation-forming clouds e.g. by Andrejczuk et al. (2010) and Franke and Raasch (2010); what distinguishes SDM however, is the probabilistic Monte-Carlo type representation of the particle coalescence process. Probabilistic representation of particle coalescence has also been recently used in atmospheric modelling studies; however, to authors' knowledge, none of these models were bi-directionally coupled with LES – see e.g. Jensen and Lee (2008) for description of an adiabatic parcel model with Monte-Carlo coalescence or Riemer et al. (2009) for description of particle-resolved aerosol transport model with Monte-Carlo coalescence but working off-line from the flow dynamics).

3. MODELLING SET-UP

All simulations in the present study were carried out using the Nagoya University Cloud-Resolving Storm Simulator (CReSS: Tsuboki, 2008, chapter 9.2 and references therein). CReSS is a non-hydrostatic compressible flow LES-type solver. Two types of moist processes representations were used: the SDM and a bulk microphysics model (Kessler-type parameterisation implemented following Klemp and Wilhelmson, 1978, section 2b). The simulations are carried out using a set-up based on the RICO composite case defined in van Zanten et al. (2011) and corresponding to atmospheric state measured and modelled in context of the Rain in Cumulus over Ocean (RICO) field project (Raubert et al., 2007). The set-up defines initial profiles of po-

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Table 1: List of model runs discussed in the paper. The run label denotes whether bulk (blk) or SDM (sdm) microphysics was used, as well as which grid resolution (coarse, middle or high) and super-droplet number density was chosen. Coarse resolution corresponds to a quarter of the domain from the original RICO set-up (i.e. grid box size of $100 \times 100 \times 40$ m with $64 \times 64 \times 100$ grid points); the middle and high resolutions denote settings resulting in halved and quartered grid box dimensions, respectively (with the domain size kept constant). For each simulation there are five time-steps defined: long and short time-step of the Eulerian component (the short one used for sound-wave terms), the time-step used for integrating the condensational growth/evaporation equation, the time-step used for solving collisional growth using the Monte-Carlo scheme, and the time-step for integration of particle motion equations.

run label	grid	dx=dy	dz	time-steps [s]	sd density [cm^{-3}]
blk-coarse	$64 \times 64 \times 100$	100m	40m	1.00/0.100 n/a	n/a
sdm-coarse-8	$64 \times 64 \times 100$	100m	40m	1.00/0.100/0.25/1.0/1.0	2.0×10^{-11}
sdm-coarse-32	$64 \times 64 \times 100$	100m	40m	1.00/0.100/0.25/1.0/1.0	8.0×10^{-11}
sdm-coarse-128	$64 \times 64 \times 100$	100m	40m	1.00/0.100/0.25/1.0/1.0	3.2×10^{-10}
sdm-coarse-512	$64 \times 64 \times 100$	100m	40m	1.00/0.100/0.25/1.0/1.0	1.3×10^{-09}
sdm-middle-8	$128 \times 128 \times 200$	50m	20m	0.50/0.050/0.25/1.0/1.0	1.6×10^{-10}
sdm-middle-32	$128 \times 128 \times 200$	50m	20m	0.50/0.050/0.25/1.0/1.0	6.4×10^{-10}
sdm-middle-128	$128 \times 128 \times 200$	50m	20m	0.50/0.050/0.25/1.0/1.0	2.6×10^{-09}
sdm-high-8	$256 \times 256 \times 400$	25m	10m	0.25/0.025/0.25/1.0/0.5	1.3×10^{-09}

tential temperature, specific humidity and wind characteristics for the trade-wind boundary layer following RICO observations (see Nuijens et al., 2009). This set-up was previously used in several modelling studies including: (Stevens and Seifert, 2008; Jiang et al., 2009; Seifert et al., 2010; Matheou et al., 2011; Grabowski et al., 2011). Here the only exception from the original set-up is the domain size – a quarter of the original domain was used (i.e. $6.4 \times 6.4 \times 4$ km instead of $12.8 \times 12.8 \times 4$ km), and the grid cell sizes – several settings were used. Tests with full domain size (not discussed herein) revealed that quartering the domain enlarges the fluctuations in time of cloud macroscopic properties; however, not to a level significant for the presented discussion.

For simulations using SDM, the initial coordinates and sizes of particles are chosen randomly with uniform distribution in physical space and bi-modal lognormal distribution in particle-size space (size spectrum as specified in van Zanten et al., 2011, section 2.2.3). All particles are initially put in equilibrium with ambient humidity assuming that all are composed of ammonium sulphate solution. The mean number of super-droplets per LES grid box varied from 8 to 512 in different simulations (see Table 1). In all calculations discussed in the paper the probability of collisions and coalescence was defined following Hall (1980, section 3d, and references therein) hence no effects of small-scale turbulence on the drop collision efficiency was taken into account.

4. SIMULATION RESULTS

A list of model runs and their corresponding labels used in the paper is given in Table 1. The SDM simulations were carried with different grid resolutions and different super-droplet number densities. The table also lists different time-steps used in the simulations - in SDM the time-steps used for the Eulerian and Lagrangian computations differ as the corresponding numerical stability constraints differ.

Following the methodology of van Zanten et al. (2011) the analyses are restricted to the last four

hours of the 24-hour model runs. Presented results are based on the LES grid data output every minute simulated time and super-droplet data (particle positions and sizes) output every 10 minutes simulated time.

4.1 CLOUD MACROSTRUCTURE

Figure 1 presents time-series of scalar quantities characterising domain-wide cloud field features: cloud cover (cc), liquid water path (LWP), rain water path (RWP) and cloud top height (zct). All quantities are labelled and defined following van Zanten et al. (2011, section 2.4.2 and Table 4 therein, and caption of Figure 1 herein). Presented time-series cover the first and the last four hours of simulations corresponding to the spin-up, and the relatively steady-state stages of the simulation, respectively. The figure is intended for comparison with analogous plots from modelling studies employing the RICO set-up: Fig. 2 in Stevens and Seifert (2008), Fig. 5 in Seifert et al. (2010), Fig. 3 in van Zanten et al. (2011), Figs 1-3,7 in Matheou et al. (2011) and Fig. 6 in Grabowski et al. (2011).

The cloud-cover (cc) plots reveal considerable dependence of cc on the choice of grid resolution, with a significant increase of cloud cover for higher-resolution simulations. This is, at least partially, caused by the definition of cc which includes an arbitrary threshold value for the cloud water mixing ratio (e.g. in a hypothetical 2×2 chessboard water content distribution with cc of 50%, downsampling to a single grid point could result in a zero cc). Furthermore, since the formation of convective clouds is triggered by vertical air motion and since refinement of the grid resolution helps to resolve in more detail the dynamics, an increase in the number of (smaller) clouds may be expected (Matheou et al., 2011, Sect. 3.2).

Liquid water path (LWP) plots show that the increase of cc with increased resolution is correlated with increase of LWP. The values of LWP obtained in middle-resolution SDM simulations (blue lines) fall within the range of values obtained with other LES from the study of van Zan-

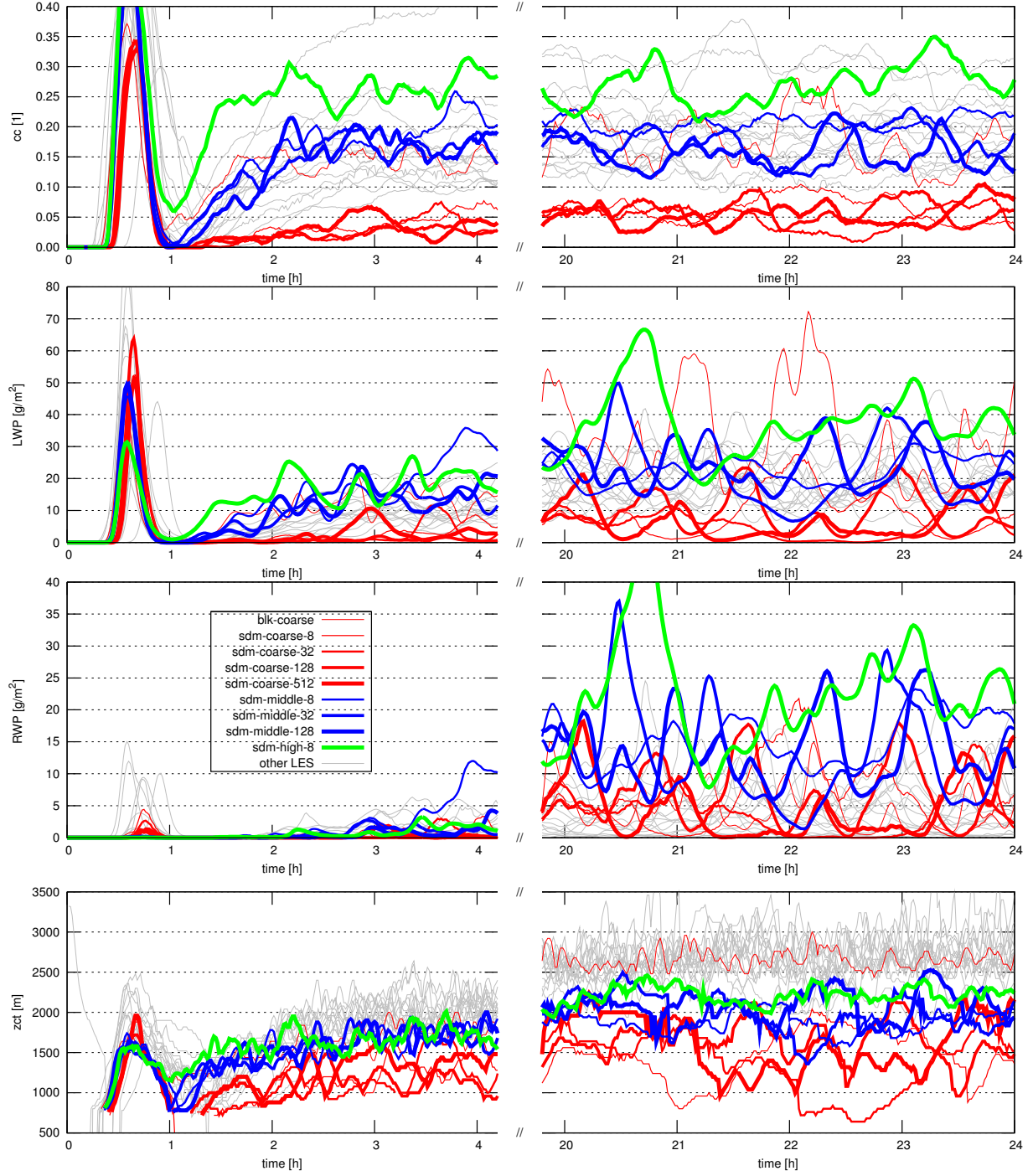


Figure 1: Time-series of cloud macrostructure characteristics defined following van Zanten et al. (2011, section 2.4.2 and Table 4 therein): (i) cloud cover "cc" is defined as the fraction of columns with at least one cloudy grid cell (a grid cell is defined as cloudy if the cloud water mixing ratio exceeds 0.01 g kg^{-1}); (ii) liquid water path "LWP" is the mean over all columns of column-integrated liquid water content (density of both cloud and rain water); (iii) rain water path "RWP" is calculated in the same manner using rain water only; (iv) the cloud top height "zct" is the height of the top of the highest cloudy grid cell. For SDM simulations the cloud and rain water mixing ratios are diagnosed by summing over the population of particles with radius smaller and larger than $40 \mu\text{m}$, respectively. In the foreground there are plots depicting data from the nine simulations listed in Table 1. In the background (plotted with thin grey lines) there are the results from LES simulations described in van Zanten et al. (2011, data obtained at: <http://knmi.nl/samenw/rico/>). See section 4.1 for discussion.

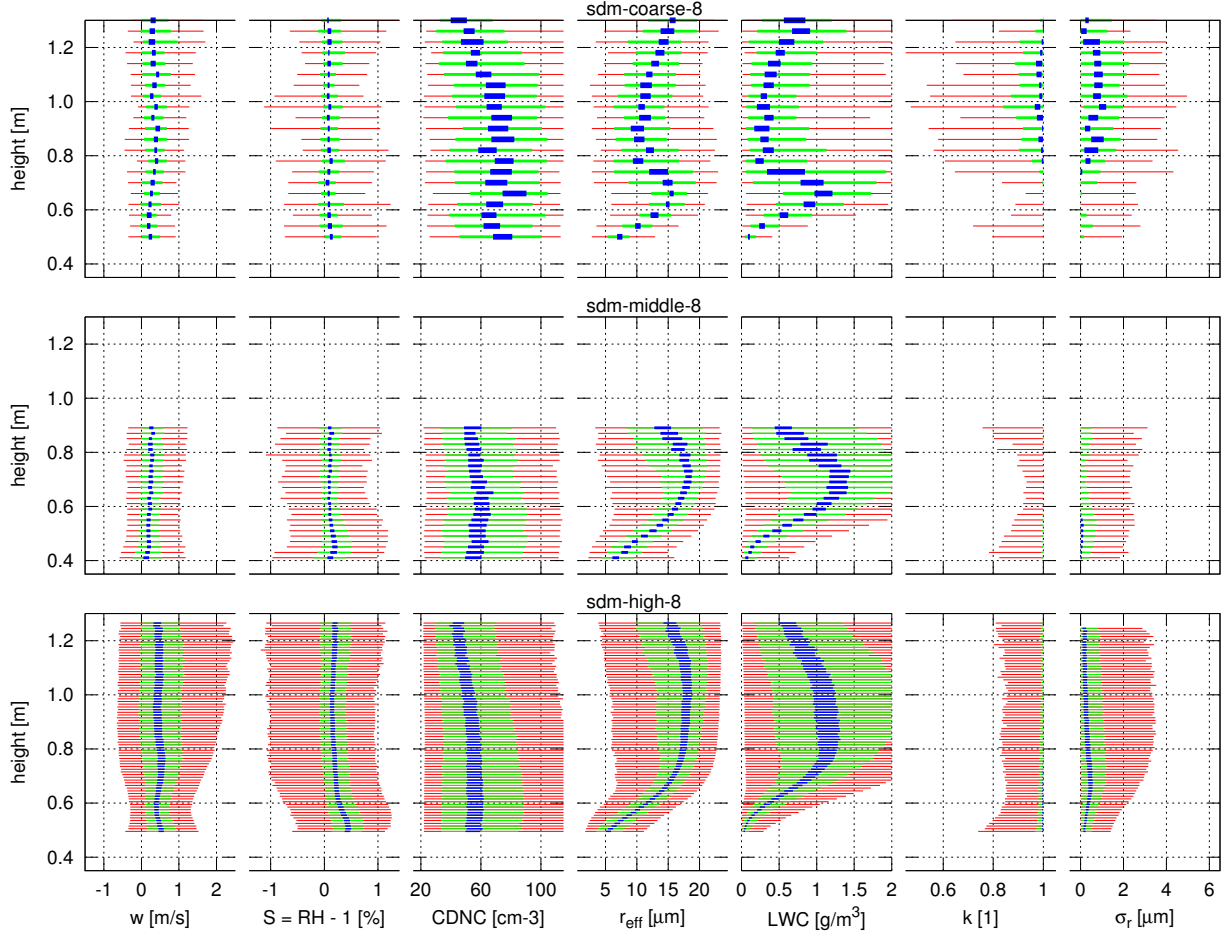


Figure 2: Height-resolved statistics of cloud droplet spectrum parameters derived from SDM simulation data. All plots in a row share the same y-axis representing height above sea level. See section 4.2 for discussion and plot construction method description.

ten et al. (2011, grey lines in Fig. 1 herein) for most of the simulated time. The high-resolution run (green line) features highest fluctuations of values of both LWP and RWP which likely corresponds to the low super-droplet density, and hence the low spectral resolution of the microphysics model.

The rain water path was one of the quantities that varied most from one simulation to another in the study of van Zanten et al. (2011, Sect. 3.2). Similarly, the hereby presented results exhibit both significant variations in RWP with simulation time as well as significant departures from one simulation to another (i.e. when changing grid resolution or super-droplet density). A notable feature is the high correlation of RWP with both LWP and cc.

The plots of cloud-top evolution with time clearly show that the SDM-simulated cloud field is shallower than the one obtained with bulk microphysics or in other LES. While the employed definition of cloud-top height does not allow direct comparisons with measurements, arguably the SDM-predicted heights for middle- and high-resolution seem more comparable to those observed during RICO (e.g. Rauber et al., 2007; Genkova et al., 2007, Fig. 1). In general, the

significant inhibition of convection in all coarse resolution runs suggest that the 100×100 meter resolution is not enough when coupled with a Lagrangian model which, among other factors, relies on LES-predicted supersaturation field directly coupled with the vertical motions.

4.2 CLOUD MICROSTRUCTURE

Figures 2,3 and 4 present height-resolved statistics of the vertical velocity w , the supersaturation S , cloud droplet concentration CDNC, droplet effective radius $r_{eff} = \langle r^3 \rangle / \langle r^2 \rangle$, liquid water content LWC, the cubed ratio of mean volume radius to effective radius $k = \langle r^3 \rangle / r_{eff}^3$, and the standard deviation of cloud droplet radius σ_r . The plots are intended for comparison with the analysis presented in Arabas et al. (2009, Figs. 1 and 2) where the data from aircraft measurements during the RICO campaign using the Fast-FSSP optical cloud droplet spectrometer (Brenguier et al., 1998) were analysed. The herein analysis of SDM simulation data is constrained to in-cloud regions defined as the grid boxes having $CDNC > 20 \text{ cm}^{-3}$ where CDNC is derived by summing over the super-droplets representing particles of radius between 1 and 24 mi-

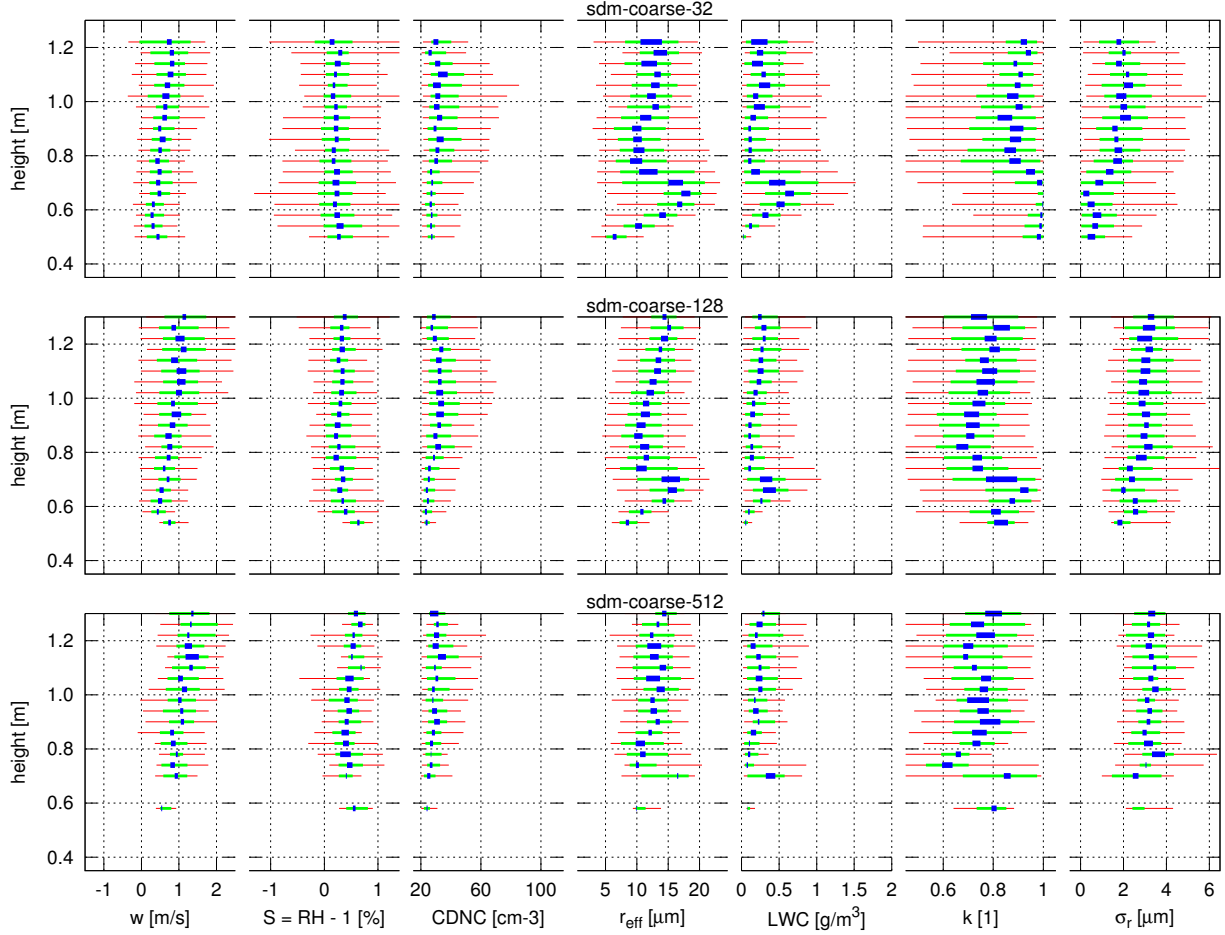


Figure 3: Same as Fig. 2 for model runs: sdm-coarse-32, sdm-coarse-128 and sdm-coarse-512.

crometers. The choices of the CDNC threshold and the spectral range correspond to those characteristic of the Fast-FSSP probe.

Plot construction method was chosen following the methodology of Arabas et al. (2009). For each level of the model grid and each plotted parameter a list of values matching the in-cloud criterion is constructed, sorted and linearly interpolated to find the 5th, 25th, 45th, 55th, 75th and 95th percentiles. The lists are constructed from the LES-grid values (w , S) or super-droplet statistics calculated for each grid cell (CDNC, r_{eff} , LWC, k and σ_r). The sample volumes are therefore defined by grid cell sizes and are of the order of $10^4 - 10^5 m^3$, while the sample volume for the 10 Hz Fast-FSSP dataset used in Arabas et al. (2009) is of the order of $10^{-6} m^3$ – a thing one has to bare in mind. The vertical extent of the measurement sample volume of ca. 10 m is comparable to the grid cell size, though. Levels with less than $0.1 \cdot N_{max}$ data-points, where N_{max} is the number of data-points at the level with the highest number of data-points, are discarded from the analysis. Finally, the 5th – 95th percentile, the interquartile, and the 45th – 55th percentile ranges are plotted as a function of height using red, green and blue bars, respectively. The pro-

files composed of the 45th 55th percentile range bars are referred to as median profiles hereinafter.

VERTICAL VELOCITY Profiles of the vertical velocity generally show a gradual increase of the spread of values with the increasing grid resolution. It is consistent with the fact that the grid acts as a spatial filter in the LES. The median profiles resemble each other regardless of the resolution suggesting that the macroscale dynamics of the simulated cloud layer are robust to both the LES grid choice and the super-droplet density choice (however, the differences in cloud-top heights plotted in Fig. 1 and evident in Figs. 2–4 reveal that this robustness is limited). The slight increase of the vertical velocities with height visible in some of the profiles, and noted in the RICO observations analysis (Gerber et al., 2008, Table. 2), may correspond to the fact that only the more vigorous updraft regions were able to produce clouds reaching the upper part of the cloud field.

SUPERSATURATION The profiles of supersaturation, especially for the high and middle resolution, show the characteristic cloud-base maxima. This confirms that the model formulation, and the time resolution used allows to capture the influence of CCN activation kinetics on the

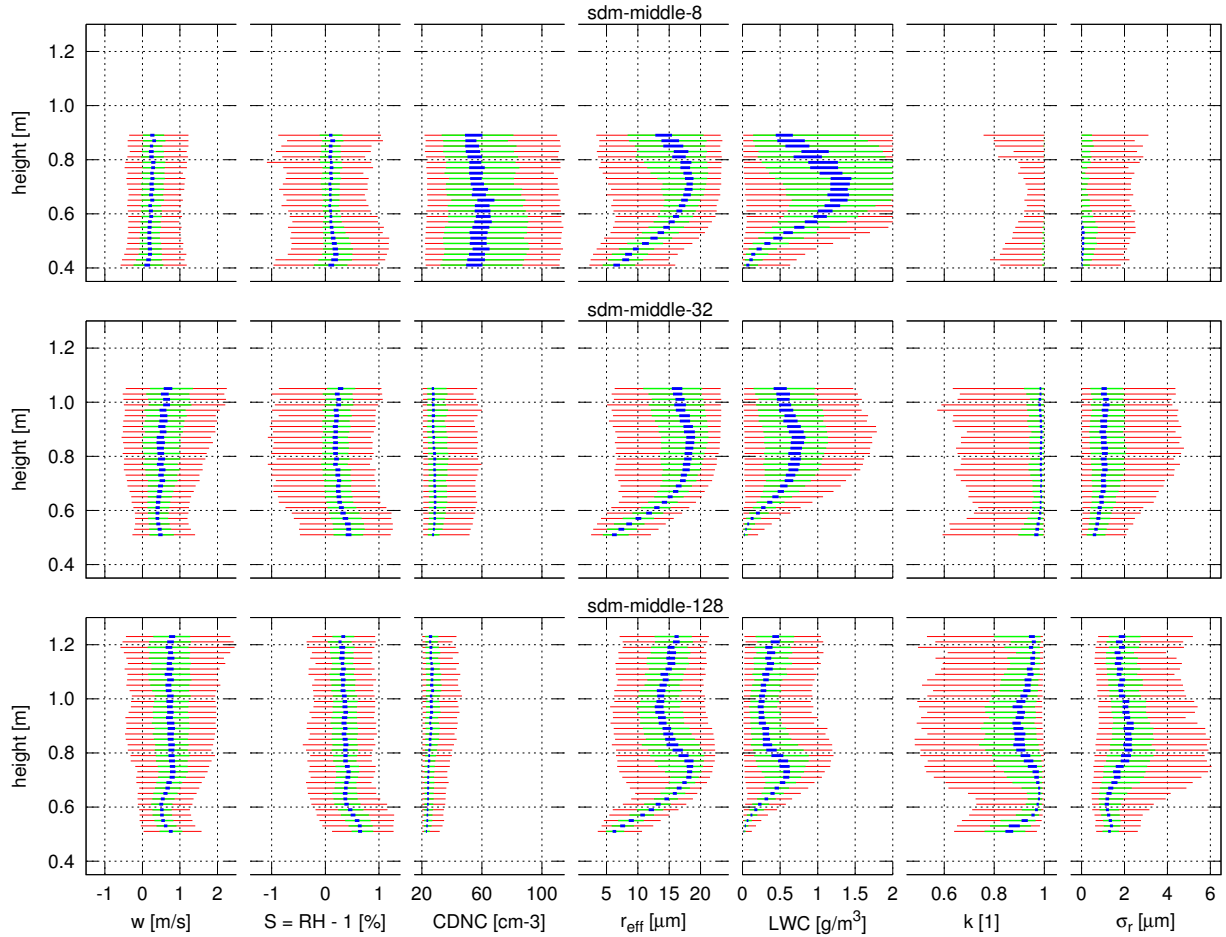


Figure 4: Same as Fig. 2 for model runs: sdm-middle-8, sdm-middle-32 and sdm-middle-128.

evolution of supersaturation. Both the values of maximal supersaturation (ca. 1%), as well as a roughly estimated supersaturation relaxation time (ca. 100s assuming ≈ 1 m/s vertical velocity, and an ≈ 100 m height scale over which the supersaturation falls off to an asymptotic value) correspond to those reported in modelling studies that employed supersaturation-predicting models (e.g. Morrison and Grabowski, 2008; Khvorostyanov and Curry, 2008). Comparison of the supersaturation prediction in the model with measurements is not viable as direct measurements of supersaturation in clouds are virtually unavailable (Korolev and Mazin, 2003). In none of the runs there is any other maximum of supersaturation visible along the profile. This suggests that the employed Lagrangian technique for representing water condensate inhibits the spurious production of cloud-edge supersaturation inherent in Eulerian models. (see Sec. 1 in Grabowski and Morrison, 2008, and references therein). The reason for it is likely (as noted as well in Andrejczuk et al., 2008, par. 10) that such coupled Eulerian-Lagrangian approach does in fact cover representation of fractional cloudiness within a grid cell.

DROPLET CONCENTRATION The range of drop concentration values obtained in the sim-

ulations does roughly correspond to the values observed during RICO and presented in Arabas et al. (2009, figure 1a), Gerber et al. (2008, figure 4) and Colón-Robles et al. (2006, figure 3). The discrepancies in the median values and the spread of CDNC among different model runs show, however, that the prediction of drop concentration is sensitive to the super-droplet density (Fig. 4). Furthermore, the higher concentrations obtained with low super-droplet densities (i.e. low spectral resolution) are closer to the observed values. The observed invariability of CDNC with height is robustly reproduced suggesting that the discrepancies are solely related to the treatment of CCN activation in the model.

EFFECTIVE RADIUS The effective radius profiles are generally robust to both grid and super-droplet density choices, and they do resemble the profiles observed with the Fast-FSSP instrument during RICO (Arabas et al., 2009, fig. 2). The profiles show a gradual increase in cloud droplet sizes from the cloud base up to the altitude of 700–800 metres where the median values of r_{eff} reach 15–20 micrometres. Above, the profiles differ more from one model run to another but still the flattening of the r_{eff} profile slope is a robust feature. The reduced slope of the median

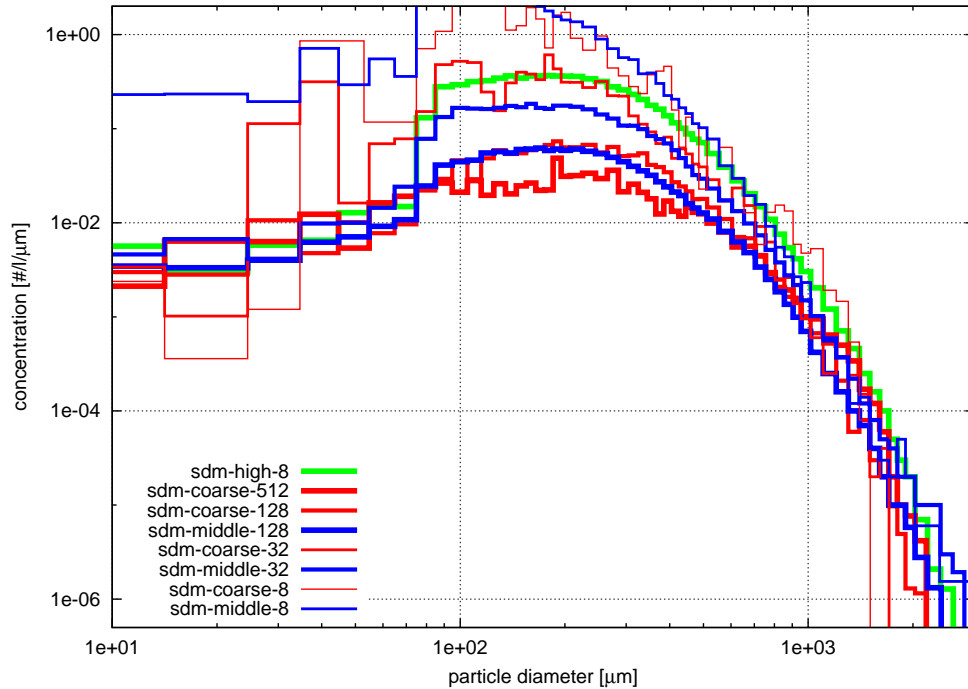


Figure 5: Comparison of model-predicted spectra for particles within size range of the OAP-2DS instrument, within grid cells with rain water mixing ratio $q_r > 0.001$ g/kg and within an altitude range of 183 ± 100 m. Figure intended for comparison with Fig. 4 in Baker et al. (2009), see section 4.3 herein for details.

profiles of r_{eff} reflects (i) the chosen drop radius range ($1\text{--}24\text{ }\mu\text{m}$ – emulating the Fast-FSSP instrument range), (ii) the decreased efficiency, in terms of radius change, of the condensational growth for larger droplets, and (iii) the increased efficiency of drop collisions reached after the initial condensational growth stage (see e.g. section 3.1 in Zhang et al., 2011, for discussion of influence of precipitation on effective radius profiles). The spread of r_{eff} values high above cloud base indicates presence of smaller droplets even near cloud top. The present analysis (and the corresponding choice of data output rate during simulations) does not provide an answer to the question of the origin of these small particles – e.g. if they were activated at cloud edges above cloud base or not (see e.g. Slawinska et al., 2012).

LIQUID WATER CONTENT LWC profiles depicted in Figures 2-4 show significant spread of values at a given level. This is in accord with RICO observations, and suggests mixing-induced dilution of cloud and the resultant decrease of water content (cf. the discussion of the adiabatic fraction profiles in Fig. 2 in Arabas et al., 2009). In SDM the condensational growth and evaporation is computed using values of supersaturation interpolated to super-droplet positions, hence the mixing scenario is not homogeneous as different droplets are exposed to different supersaturations within a single grid cell.

The decrease in LWC in the upper part of the cloud is correlated with an increase of rain water mixing ratio (not shown). In the lower part of the cloud, the median profiles of LWC obtained

in the simulation with middle and high grid resolution show arguably reasonable agreement with LWC profiles derived from RICO observations depicted in van Zanten et al. (2011, Fig. 8), Gerber et al. (2008, Fig. 1) and Abel and Shipway (2007, Fig. 7) taking into account that the referenced observations were taken with different instruments having different sampling rates and spectral ranges.

PARAMETER K Most GCMs employ a parameterisation of the effective radius when diagnosing the cloud optical depth of clouds from predicted liquid water content and drop number concentration (see e.g. section 2 in Brenguier et al., 2000, and references therein). Typically, the cubed ratio of the mean volume radius to the effective radius $k = \langle r^3 \rangle / r_{eff}^3$ (or a similarly defined scaling coefficient) is assumed to be constant or to depend solely on drop concentration (e.g. Peng and Lohman, 2003). Value of $k = 0.8 \pm 0.07$ based on aircraft observations in maritime clouds using an FSSP-type instrument reported in Martin et al. (1994) is often used in climate models.

As shown in Figure 2, all simulations with the mean value of 8 super-droplet per LES grid cell predict values of k hardly different from unity. This means that the effective radius is in most cases equal to the mean volume radius, as it should be, taking into account that the 8 super-droplets (which may be thought of as size bins) are used to represent a wide spectral range of particles: aerosol, cloud, drizzle and rain; while the statistics presented in the plot cover a narrow

spectral range. Consequently, cloud water is likely represented by a single super-droplet (bin) in each grid cell, a situation in which all of the cloud droplets would have the same size and $k = 1$ by definition. The values of the k parameter calculated in the model runs with mean super-droplet density of 128 range from approximately 0.6 to 0.9. There is no significant difference when the super-droplet density is increased to 512 suggesting that the density of 128 per cell is enough to resolve the relevant cloud droplet size spectrum features.

DROP RADIUS STANDARD DEVIATION

In consistency with the aforementioned behaviour of k for low super-droplet density, the drop radius standard deviation σ_r hardly differs from zero when a mean of 8 super-droplets per cell is used, and it still goes down to zero at some levels with a mean of 32 super-droplets per grid cell. For all higher spectral resolution simulations the 5th percentile of σ_r is greater than zero at all levels, and the increase of mean super-droplet density from 128 to 512 does not influence the profile shape. In general agreement with RICO observations, the standard deviation ranges from 1 to 6 micrometres. The profiles of σ_r show a slight increase with height (best captured in the sdm-middle-128 run); however, the observed inclination of the σ_r profiles resembles more the 95th percentile profile derived from SDM simulations. The fact that the values of σ_r are larger than those obtainable in adiabatic drop growth process (see e.g. Yum and Hudson, 2005, and references therein) suggests that the model does capture to some extent the mixing-induced broadening of the cloud droplet spectrum. However, since the mixing in SDM is limited to LES-resolved motions with characteristic length scales constrained by grid cell dimensions, the level of agreement with observations is, as expected, limited.

4.3 PRECIPITATION MICROSTRUCTURE

The analysis depicted in Figures 2, 3 and 4 concerned the cloud-droplet region of the particle size spectrum. A comparison of model-predicted spectra for larger particles is depicted in Figure 5. The figure is intended for comparison with Fig. 4 in Baker et al. (2009) based on measurement data obtained with the OAP-2DS instrument (Lawson et al., 2006) during RICO research flights. During RICO the OAP-2DS instrument was set to classify particles into 61 size bins spanning the $2.5 \mu\text{m} - 1.5 \text{ mm}$ size range in radius. In the analysis of Baker et al. (2009) a mean size spectrum was derived from 237 spectra measured within rain-shafts below the cloud base at the altitude of about 183 metres (600 ft). In order to derive comparable quantities from the SDM simulation results, the super-droplets in each grid cell were classified into size bins of the same layout as used by the OAP-2DS instrument, an altitude range of $183 \pm 100 \text{ m}$ was chosen, and only grid cells with rain water mixing ratio $q_r > 0.001 \text{ g/kg}$ were

taken into account (q_r being derived from summation over super-droplets representing particles with radii greater than $40 \mu\text{m}$). A comparison of Figure 5 with Fig. 4 from Baker et al. (2009) (both plots share the same axis ranges) reveal that the model results, regardless of the grid-resolution or super-droplet density choice, show fair agreement with the measurement results for drop diameters greater than 0.1 mm . The spectrum from the sdm-coarse-512 run (with the highest spectral resolution and the best Monte-Carlo sampling density) resembles most closely the measurements having the lowest concentrations in the $0.1\text{--}0.4 \text{ mm}$ diameter range. All simulations disagree markedly with the measurements within the $10\text{--}20 \mu\text{m}$ diameter range. These measured particles within this range were "most likely deliquesced aerosols" (Baker et al., 2009) and since there are no aerosol sources in the model, this disagreement is still a plausible result. The drop breakup process was identified as another possible source of droplets smaller than $100 \mu\text{m}$, and this process is also not included in the present version of the model. Moreover, it was the lack of hydrometeors smaller than 100μ in diameter that was considered as the primary highlight of the observations reported in Baker et al. (2009), and this feature of the spectrum is in fact hinted in the simulation results.

5. SUMMARY

The salient features that distinguish SDM from bulk and bin warm-rain microphysics models are: (i) diffusive error-free computational scheme for both condensational and collisional growth; (ii) particle spectrum representation allowing straightforward comparison with experimental data obtained with particle-counting instruments; (iii) persistence of arbitrary number of scalar quantities assigned to a super-droplet (e.g. chemical properties); (iv) scalability in terms of sampling error (i.e. super-droplet density); (v) parameterisation-free formulation of the key processes involved in cloud-aerosol interactions.

The last feature, in particular, does not come without its challenges. Explicit treatment of aerosol microphysics implies taking care of their budget within the simulation domain, including modelling their sinks (wet and dry deposition) and sources, the latter not being represented in the present study.

The other two processes not represented in the discussed simulations are: (i) the impact of turbulence on drop collisions (see e.g. Devenish et al., 2012), and (ii) the influence of drop breakup on the size spectrum of precipitation particles (see e.g. Villermaux and Bossa, 2009). Yet, the arguably fair level of agreement of the simulation results reported herein and the previously published in-situ measurement results from RICO, suggest that the set of processes represented in the present set-up of SDM includes at least the

key players involved in determining the features of the size spectra of cloud and precipitation particles. One has to bare in mind that a direct comparison of RICO measurement data with LES results of the type presented herein is not possible due to different time- and space- scales associated with the model variables and the measurements, as well as due to the nature of the "composite" modelling set-up. (typical atmospheric conditions, with the diurnal cycle neglected in particular).

The SDM modelling approach offers the unique possibility to mimic in the analysis the particle-counting process inherent in the principle of operation of most airborne aerosol, cloud and precipitation probes. As a result, it becomes meaningful to analyse such model-predicted cloud droplet size spectrum parameters as e.g. k or σ_r , not taken into account in previous comparisons of RICO LES results with aircraft observations (Abel and Shipway, 2007; van Zanten et al., 2011). What militates in favour of pertinence of the obtained results is that the present model employs fewer parameterisation (in comparison with bulk or bin models) and more basic principles to describe processes occurring at the microscale (e.g. description of the Köhler curve shape as opposed to employment of such parameters as the exponent in Twomey's formula for CCN activation parameterisation in bin models, or the autoconversion threshold in Kessler-type bulk models).

The key conclusion from the presented analysis is that while the convergence of the macroscopic cloud parameters do not seem to get any better than in the other LES simulations using the RICO set-up, the SDM is able to provide more detailed insight into cloud microstructure, and thus indirectly into its optical properties.

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